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A Field Guide to Plasma Source Ion Implantation

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Introduction

Plasma source ion implantation is a surface modification technique designed to provide inexpensive, high-throughput ion implantation for improved wear and corrosion resistance. With PSII entering commercialization, there exists a need to understand the physics of the process and the implications on manufacturing system design and product throughput. This paper represents an effort to explore these issues.

Overview of Ion Implantation

Ion implantation is a method of modifying the electrical, chemical and mechanical properties of the near surface (<1μm, 40 micro-inch) layer of materials. High energy ions striking a surface become buried beneath the surface. The implanted ions cause changes in the material structure and can combine with other elements to produce hard compounds (e.g. CrN) and/or low friction surfaces, which can improve the wear lifetime of manufacturing tools and manufactured components. Advantages of ion implantation over other surface modification include its ability to provide implanted atomic concentrations above limits imposed by chemical solubility, at low temperature without causing dimensional changes.

The depth of the implanted layer is a function of the ion species and the target material. The implanted layer thickness can be increased by increasing the implantation energy and choosing ion implantation techniques that implant the ions along perpendicular trajectories relative to the surface. PC-based ion implantation simulation programs, which predict the implanted layer thickness, are commercially available.

An undesirable side effect of ion implantation is surface sputtering. Sputtering is the removal of material from the surface due to low energy ions or ions which strike the surface at glancing angles. There is always a competition between implantation and sputtering. As the number of incident ions is increased, eventually a balance will be reached between ions which are implanted and previously implanted ions (along with target material) which are removed by sputtering. The level of this balance is referred to as the sputter-limited retained dose. Once this dose (measured in atoms per square centimeter) is reached, further implantation does not yield a higher retained dose, but only gives further surface recession. The retained dose would be higher for high energy ions and for ions which impact the surface at non-glancing angles.

Implantation of Hard Cr Plating

Improvements in the wear life of nitrogen implanted, Cr-plated components is well demonstrated in the literature and in actual industrial applications. There is a general correlation between increasing surface hardness and increasing wear lifetime. Conservatively, the increase in wear lifetime is 10 times the increase in surface hardness. For example, a 20% increase in surface hardness can result in a 200% increase in the wear lifetime. These results can be used to plot a strategy for a particular application. For example, a customer specifies a desired increase in the wear lifetime, which corresponds to an increase in surface hardness, which can be produced by implantation parameters interpolated from data available from the open literature. A 200% increase in wear lifetime can result from a 20% increase in surface hardness which requires 60 keV N^+ and a dose of at least $5x10^{17}$ atoms/cm^2.

Conventional Beamline Implantation

Conventional beamline ion implantation was developed in the late 1950's to change the electrical properties of semiconductor materials. The process consists of producing and accelerating ions, mass-analyzing the ions (if desired), accelerating these ions through a series of grids, and scanning the beam across the target using electrostatic raster plates. Beamline implantation results in a beam of known ion energy and composition (if magnetic mass analysis is used). This process is inherently line-of-sight and works optimally for planar targets.

For applications of ion implantation to non-planar targets, conventional beamline systems have limitations. The target to be implanted must be manipulated in a vacuum environment in order to implant the entire surface. Ions which strike the target surface at glancing angles will sputter previously implanted material. This can be mitigated by masking areas of the target, but at the expense of throughput and beam utilization.

Plasma Source Ion Implantation

In PSII, the target to be implanted is immersed in a plasma and repetitively pulsed to a high negative voltage. An expanding boundary layer (sheath) forms around the target during the voltage pulse. The electric field within this expanding sheath accelerates ions toward all target surfaces simultaneously, eliminating the need for target manipulation or masking. This allows a more uniform implant, and it also allows the treatment of a variety of shapes without a complex refixturing effort. A disadvantage of this process is that the ion energy and species can not be selected as in magnetically filtered beamline implantation, since the negative voltage pulse applied to the target attracts all positively charged ions in the plasma.

Sheath Physics

To better understand the sheath dynamics, the expansion process must be examined step by step (see Fig. 1).

When a pulse of negative voltage is applied to a conducting target immersed in a plasma (a neutral collection of positive ions and negative electrons) the plasma electrons are quickly repelled by the negative voltage on the target. On a very short time scale (a few nanoseconds), the much more massive positive ions are unable to respond to the applied voltage. These motionless positive ions shield the negative voltage on the target from the rest of the plasma. The electrons will recede to a position where the negative voltage on the target is completely shielded by the uncovered ions. The resulting region of space near the target containing only ions is known as the ion matrix sheath. Since the target is at high negative voltage and the bulk of the plasma is near ground potential, the ion matrix sheath contains a large electric field.

On a longer timescale (on the order of a few hundred nanoseconds), the massive ions within the ion matrix sheath begin to respond to the electric field in which they find themselves. These ions are accelerated toward the target, resulting in the desired implantation. As the ions are collected by the target, the pulse modulator works to maintain the negative voltage at the same level. The loss of the collected ions from the sheath means that the voltage is not completely shielded and the plasma electrons will recede

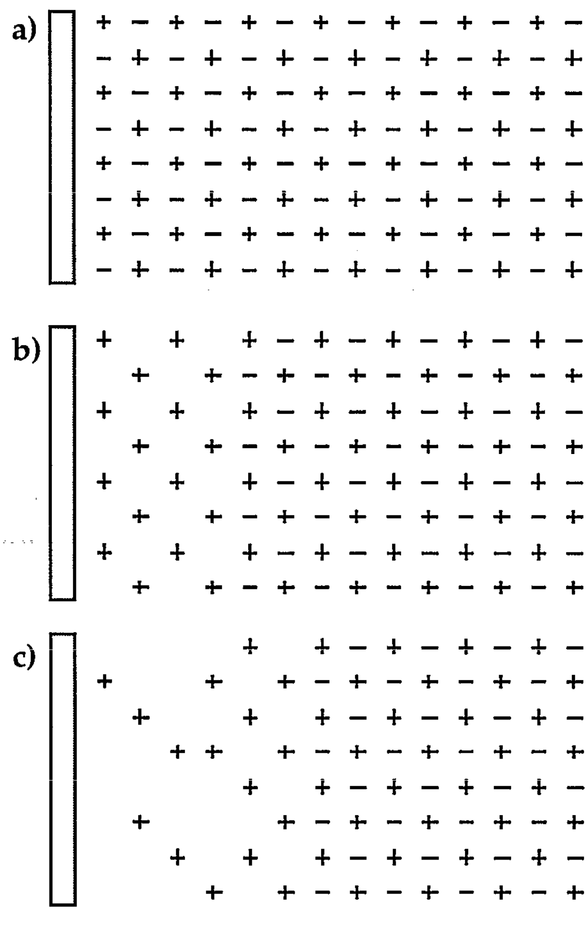

Fig. 1 Schematic of sheath expansion. The implantation target is shaded, ions are shown as (+) and electrons are shown as (-). a) Neutral plasma before voltage is applied to target has an equal number of ions and electrons. b) Less massive than the ions, the electrons are able to respond quickly and are repelled by the negative voltage applied to the target, creating the ion matrix sheath. c) As ions respond, they are absorbed by the target causing electrons to recede further from the target resulting in continuous sheath expansion.

to uncover more ions to provide the required shielding. This process of ion collection and electron recession results in expansion of the sheath. The results of calculations of sheath expansion and current collection are shown in Figs. 2 and 3, respectively.

For a given pulse length, the rate of sheath expansion will determine the ultimate sheath extent and the conformality of the resulting implant. The rate of sheath expansion depends on several parameters. The expansion rate varies directly with target voltage and inversely with plasma density and ion mass. Since the voltage and ion species are usually fixed by materials considerations, plasma density adjustments are made to control the sheath expansion.

There are several constraints on the size of the expanding sheath formed during pulsed implantation. The final sheath extent should be small enough that it does not intersect the vacuum chamber walls, which could result in loss of implant uniformity. Similarly, in batch implantation, the sheaths from neighboring targets should remain separate. Another consideration is that of collisionality. Ions traversing the sheath can collide with neutral gas molecules and lose energy, lowering the effectiveness of the implant. The sheath dimension should be kept smaller than or at least equal to the collision mean-free path.

The issue of sheath conformality must also be addressed. If the sheath is allowed to grow large compared with the features of the component to be implanted, the conformality and resulting uniformity will be compromised. Finally, the pulse repetition frequency must be kept low enough to allow the plasma sufficient time to fill in the sheath following the high voltage pulse.

PSII Hardware

A PSII system consists of a vacuum system, a plasma source, a pulse modulator, controls and diagnostics. This section describes the basic requirements for each of these subsystems.

Vacuum system

The vacuum chamber must be large enough to contain the components to be implanted while also containing the plasma sheath which surrounds each component during application of the high voltage pulse. A forepump (and perhaps Roots blower) is required to remove the atmosphere (760 Torr at sea level) to a level where a diffusion, turbomolecular or cryo pump can be used (~0.1 Torr). The vacuum chamber is then evacuated to moderate vacuum (~1×10^{-6} Torr) to ensure purity of the implanted species. The gas precursor for the plasma is typically

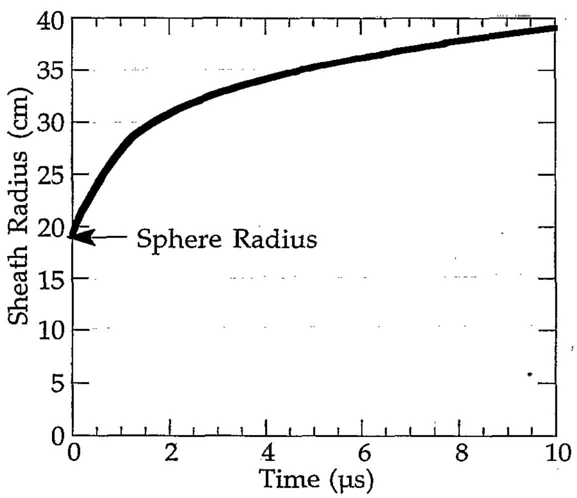

Fig 2 Calculated sheath expansion for a 19 cm radius spherical target, 80 kV target bias, 1 µs rise time, 2×10^9 ions/cm^3 plasma density.

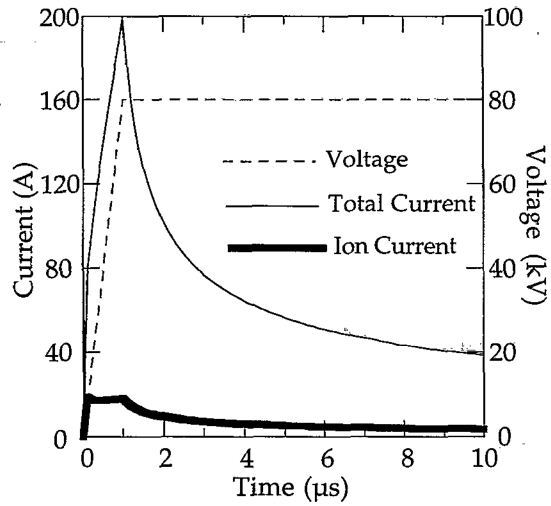

Fig. 3 Calculated voltage and current waveforms for a 19 cm radius spherical target, 80 kV target bias, 1 µs rise time, 2×10^9 ions/cm^3 plasma density. The total current is the sum of the collected ions and secondary electron emission.

continuously flowing through the chamber with a pressure necessary to provide sufficient plasma density without causing undesired collisions of the background gas with the accelerated ions. The operating pressure is typically ~2x10^{-4} Torr. Since a portion of the total processing time is spent evacuating the chamber, it is important to have pumps of sufficient size so as not to adversely affect throughput.

Another component of the vacuum system is the implantation target stage. The stage allows electrical connection of the implantation targets to the pulse modulator, while insulating the target from the chamber walls. The pulsed voltage is fed into the chamber by an electrical feedthrough which is vacuum tight. Usually, some type of cooling (flowing water or oil) is required to keep the components and feedthrough from overheating during implantation.

Plasma source

The plasma source must produce a plasma of the proper species for implantation (for example, nitrogen) with sufficient uniformity to assure a uniform dose to the implanted component. The plasma density (number of ions per cubic centimeter) must be high enough that the resulting plasma sheath yields as conformal a sheath as also required to sufficient dose uniformity. Several types of plasma sources are commercially available. These include capacitively and inductively coupled radio frequency (rf) and microwave sources. These types of sources vary in cost, complexity, ultimate plasma density, plasma uniformity, ion species composition and efficiency.

Besides cost, perhaps the most important characteristic of a plasma source is the ion species composition. The negative, high voltage pulse applied to the target attracts all positively charged ions that appear within the ultimate sheath extent. In a nitrogen plasma, these ions could be molecular (N_2^+) or atomic (N^+). For a 50 kV implant, both types of ions will be accelerated through the sheath to the same (50 keV) energy. However, upon impact with the surface the N_2^+ ion will dissociate into two 25 keV ions. These low energy ions result in a shallow implant, surface sputtering, low retained dose, and in some cases an unacceptable implant. The ion species mix varies with source type, rf frequency and power as well as operating pressure.

Pulse modulator

The pulse modulator can be broken down in to a high voltage dc power supply, and a switch. The size of the high voltage power supply combined with the desired implant dose provides the ultimate determination of throughput. Typically, the power supply is used to charge capacitors or a pulse forming network to the required voltage. The stored charge is delivered to the load through a high voltage, high current switch. In some cases a pulse transformer is used to boost or reduce the voltage applied to the target.

Several options for high voltage switching technology exist. Solid state modulators are good candidates for low voltage applications. They are simple, reliable, flexible and economical. For higher voltage operation vacuum tube and gaseous switch tube technologies are commercially available.

Design considerations for the pulse modulator focus on the rise time of the voltage waveform during implantation. As shown in Fig. 3, a large amount of the ion current is collected during the initial phase of the high voltage pulse when the sheath is growing at a high rate. If the risetime of the voltage is slow, the ions collected at early times will be of low energy and cause excess sputtering and a lower retained dose.

For large area implants, a modulator must be chosen with a high peak current capability, since a large current is collected during the voltage rise. If the peak current limit is too low, a large area implant must be performed at low plasma density, resulting in a large sheath and poor implant uniformity. If the current limit is such that the sheath is larger than the vacuum chamber dimensions, there will be no window in which to operate. (This is discussed further in the throughput example below.)

Other considerations for pulse modulator design include pulse repetition frequency, cost, reliability, factory floor "footprint" and the ability to handle the variety of load impedances presented by the variety of plasma densities, target areas and component geometries.

Controls and Diagnostics

A PSII system should have sufficient controls and diagnostics to ensure safe and reliable operation. Safety interlocks should be provided to ensure that personnel do not come into contact with high voltage or enter areas of high x-ray flux. Other interlocks should ensure that sufficient cooling of the modulator, vacuum chamber and target stage exist prior to operation. Desirable diagnostics include the ability to continuously monitor pulse repetition frequency, current and voltage waveforms, target temperature, x-ray radiation levels and plasma density.

The bad news: Secondary electron emission

An important problem associated with PSII is the emission of secondary electrons produced by high energy ion bombardment. The ions which strike the target surface deposit a large amount of energy in the near surface layer. This energy goes into heating of the target and also causes the emission of electrons from the target surface. For example, a 40 kV argon ion incident on stainless steel has an emission coefficient of 5 (5 electrons are emitted for each incident argon ion). Since the ions and electrons have opposite charge, the emitted *negative* electrons are accelerated *away from* the target in the same electric field that accelerated the *positive* ions *toward* the target.

This current of high energy electrons causes several problems. First, the flow of ions and electrons both represent current that must be provided by the high voltage power supply. In the above example of a 40 kV argon implant, five-sixths of the current is carried by the electrons while only one-sixth of the current is ion flow to the target. This means that only 16% of the power goes into ion implantation and the rest goes into the electrons. This requires a much larger power supply than would be needed to supply the ion current alone, because 84% of the electrical power is wasted. These emitted electrons strike the vacuum chamber wall where they create heat (which must be removed by active cooling in high power systems) and x-rays (which require additional lead shielding in high voltage systems).

Several schemes for mitigating the effect of electron emission are under investigation such as magnetic or electrostatic confinement of the emitted electrons.

Limits on throughput

The throughput of a PSII device is determined by the rate at which ions are incident on the target, the desired dose, and the total surface area to be implanted. To first order, throughput is then simply a function of total power divided by target surface area. Other throughput limitations such as sheath size and peak current are discussed in the next section.

The formula for minimum process time is given by

$$T=\frac{AD(1+\gamma)e}{(P/V)\eta}$$

where T is the process time in seconds, A is the target area in cm^2, D is the desired dose in atoms/cm^2, γ is the electron emission coefficient (usually between 5 and 10), e is the electron charge in Coulombs, P is the total time averaged power delivered to the target in Watts, V is the implant voltage, and η is the number of atoms per incident ion (2 for N_2^+). With dose, voltage, electron emission and species composition fixed by materials and plasma constraints, implant time is determined by the target area divided by system power. The total time to implant a batch of components will be larger than that given above due to inefficiency of the power supply, implantation of ions into the target fixturing, and time for loading, pumping and unloading of components.

By assuming an emission coefficient of 10, a dose of $3x10^{17}$ atoms/cm^2, an implant voltage of 80 kV, and 2 atoms per ion, the above equation gives a maximum implantion throughput rate of 0.047 cm^2/sec/kW (i.e. a 100 kW system could process a maximum of 4.7 cm^2/sec).

To avoid a reduction in pulse repetition frequency and a resulting loss in throughput, sufficient cooling of the implantation targets and vacuum chamber is required for high power systems. The power delivered to the target must be balanced by sufficient cooling so that target heating does not damage the bulk material by annealing previous heat treatments or causing thermal distortion. Also, as a general rule of thumb the heat loading should be kept below W/cm^2 to avoid overheating the treated part. It is difficult to remove more than 1 W/cm^2 through a water cooled fixturing system in the vacuum environment of PSII. Active cooling of the chamber walls may also be required to balance heating due to secondary electron emission.

A Practical Example

To first order, throughput is simply a function of total available power divided by target area. In this section, we explore two more subtle limitations on throughput: (1) to avoid non-uniformity of ion dose, the sheath from each target must be small enough so it does not intersect either the vacuum chamber walls or sheaths from other targets; and (2) the peak current (sum of the collected ion current and emitted electron current) during the pulse cannot exceed the limit imposed by the pulse modulator design.

This section examines the theoretical throughput of a moderately sized PSII system constructed by North Star Research Corporation (NSRC) for the world's first commercial facility operated by Empire Hard Chrome, Chicago, IL. The specifications of the NSRC implanter are as follows:

Vacuum system:	39 in. diam., 39 in. long aluminum cylinder with stainless steel liner, oil diffusion pump
Plasma source:	200 kHz rf source with an immersed coil antenna
Pulse modulator:	80 kV, 100 A total pulsed current with peaks of 200 A, 10 μs pulse length, 400 Hz pulse repetition rate, 25 kW total power

Results of numerical calculations of sheath propagation and current collection for a nitrogen (N_2^+) implant of two target geometries will be discussed in this section: a spherical target 19 cm in radius and set of cylindrical targets 5 cm in radius and 20 cm in length. Conditions used in the simulations were: implanted species was N_2^+, the pulse length was 10 μs, the electron emission coefficient was assumed to be 5 at 20 kV (varying as the square root of the target voltage), the peak target voltage was 80 kV with a 1 μs rise time. These calculations are meant to be purely illustrative and should be used to observe trends only.

The sheath radius at the end of the pulse and the peak total current are shown as a function of plasma density in Fig. 4 as predicted by a sheath expansion model for the spherical target. The final sheath extent decreases with increasing plasma density, while the peak current increases with increasing plasma density.

An operating window can be identified by taking into account the constraints on sheath size and peak current. The sheath should remain small enough that it does not impact other targets or the chamber walls. Since we are only concerned with one target in this case the sheath must be smaller than the chamber size. For the ~100 cm (39 in.) diameter chamber, this means the sheath radius must be less than 50 cm constraining the plasma density to be greater than 4×10^8 ions/cm^3.

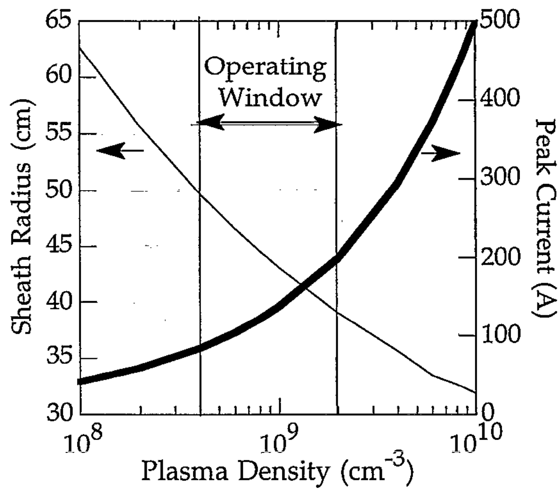

Fig. 4 Final sheath extent and peak current as a function of density for a 19 cm radius spherical target. To satisfy the constraints of 200 A peak current and 50 cm sheath radius, the operating density must lie between 4×10^8 and 2×10^9 ions/cm^3.

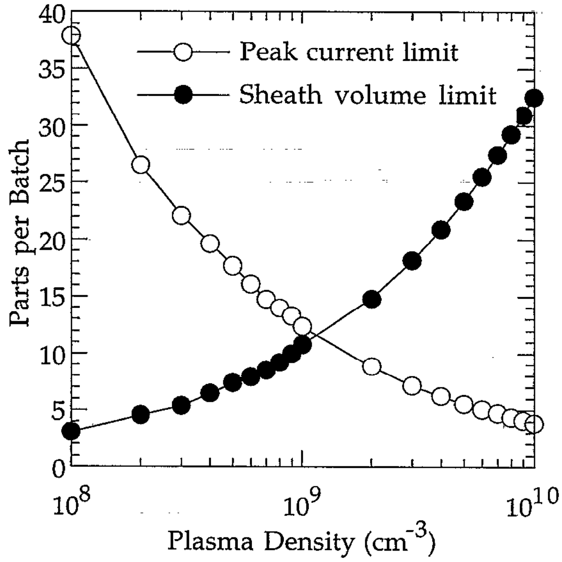

Fig. 5 Number of 5 cm radius, 20 cm length cylindrical parts which can be included in a single batch in the North Star/Empire Hard Chrome PSII system determined by the modulator peak current and the sheath volume limit.

Table I
Throughput optimization calculations for North Star/ Empire PSII system

Plasma density (10^8 ion/cm^3)	5	10	50
Final sheath radius (cm)	29	24	16
Peak total current (A for 1 target)	30	43	96
Ave. ion current (A for 1 target)	0.4	1.5	3.3
Batch size	7	11	5
Dose per pulse (10^{11} atoms/cm^2)	2.2	3.0	6.6
Energy per pulse (J)	67	150	144
Pulse frequency (Hz)	372	167	174
Heat loading (W/cm^2)	1.0	0.6	1.5
Implant time (hr)	1.0	1.7	0.7
Total process time (hr)	2.0	2.7	1.7
Time spent implanting (%)	51	63	42
Throughput (targets/hr)	3.5	4.1	2.9

The maximum current that can be supplied by the modulator during the pulse is 200 A, which constrains the plasma density to be less than 2×10^9 ions/cm^3.

In some cases (i.e. large targets) these two constraints will be such that no operating window exists. The data presented in Fig. 4 shows that a service center with highly variable products requires a high current modulator along with a high density plasma source capable of controlled operation at varied densities.

Fig. 5 shows results of sheath expansion and other calculations to determine the number of targets that can be included in a single batch in the North Star/Empire Hard Chrome PSII system for a range of plasma densities. A cylindrical target 5 cm radius and 20 cm length was used in the calculations.

The sheath model was used for a single target to predict the final sheath extent and peak current drawn during the high voltage pulse. Then using the volume of the sheath around the target and the vacuum chamber volume the maximum number of targets which could be contained was computed for a given plasma density. Similarly, using the peak current drawn by a single target and the maximum current that can be delivered by the modulator, the maximum number of targets which can be implanted was determined. As shown by Fig. 5 the maximum number of targets limited by the peak current decreases with increasing plasma density. The maximum number of targets determined by the sheath volume limit increases with increasing plasma densities. These two intersecting limits give a maximum of 11 targets for these conditions that can be implanted while satisfying both constraints of non-intersecting sheaths and total modulator current. The result of this calculation is however a theoretical maximum since the targets must be fixtured to a water cooled frame which will also draw current and have its own sheath.

With the information generated in Fig. 5, we can now begin to look at the optimum batch size for the system. Table I gives results of theoretical throughput calculations for three different plasma densities shown in Fig. 5. The table gives the final sheath radius, ion dose per pulse, peak total current and average ion current for *one* target calculated by the sheath expansion model. The batch size comes from Fig. 5 (the lesser of the peak current and sheath volume limits.) The energy per pulse is the product of the batch size, the

Table II
Effects of PSII system upgrades on throughput

	A	B	C	D
Modulator current limit (A)	200	200	2000	2000
Total system power (kW)	25	25	100	100
Vacuum chamber volume (l)	780	8000	780	8000
Optimum plasma density (10^8 ion/cm^3)	10	1	100	10
Final sheath radius (cm)	24	45	14	24
Batch size	11	31	33	110
Heat loading (W/cm^2)	0.6	0.2	0.9	0.3
Implant time (hr)	1.7	4.8	1.2	4.2
Total process time (hr)	2.7	5.8	2.2	5.2
Fraction of time spent implanting (%)	63	83	55	81
Throughput (targets/hr)	4.1	5.3	15	21

average current, the voltage and pulse length. The pulse frequency is simply the total system power (25 kW) divided by the energy per pulse. The heat loading is the total ion power divided by the total batch area. The implant time is computed from the desired incident ion dose (3×10^{17} atoms/cm^2), the dose per pulse and the pulse frequency. The total process time is the sum of the implant time and the time to vent the chamber, unload and load a batch and pump the chamber to base pressure (assumed to total 1 hour).

Table I shows that the maximum throughput occurs at the density (10^9 ion/cm^3) that allows the largest batch. Although the smaller batches have shorter implantation duration, the time required for pumpdown, venting, loading and unloading drives the overall throughput down. The highest throughput occurs when the fraction of time spent performing actual implantation is maximized. The 4.1 targets per hour represents 2600 cm2/hr which is less than the predicted maximum throughput of 4300 cm2/hr for a 25 kW system. The failure to perfrom at the maximum throughput is due to the influences of limitations in peak current and vacuum chamber size.

While Table I shows the optimum throughput for a given set of conditions, other considerations must be made when choosing the operating point. For certain applications, the 21 cm sheath radius (16 cm from the surface of the 5 cm cylinder) will be too large to uniformly implant a convoluted surface. In this case, one may opt for a lower throughput at a higher density to get a more conformal sheath and a higher quality implant. The third column of Table I gives a heat loading of 1.5 W/cm^2 (greater than the 1 W/cm^2 rule of thumb) indicating an implant at full power at 5×10^9 ions/cm^3 is not acceptable.

Through an analysis similar to that used in Table I we can also explore the effect on throughput of upgrading system hardware. Table II shows results of calculations in which the pulse modulator is upgraded by increasing peak current and total power and the vacuum chamber is enlarged. For these cases the optimization process performed for Table I is repeated for each system configuration (i.e. the maximum throughput is found by varying the plasma density for each system).

Column A of Table II is reproduced from the optimized throughput of Table I which had a vacuum chamber 780 liters and a 25 kW pulse modulator with a 200 A peak current capability. Column B gives the optimum throughput for a case in which the vacuum chamber size is increased by a factor of ten to 8000 liters. Column C uses the base vacuum size of 780 liters with a 100 kW modulator with a peak current of 2000 A. Column D is based on a “super system” with a 8000 liter vacuum chamber and a 100 kW modulator with a 2000 A peak current. These upgrades were chosen only to illustrate the effects that large changes in system architecture would have on throughput. In determining the best system for a given facility one must take into account several factors including the demand for implanted parts and the capital and operating costs of the upgraded systems.

The effect of increasing vacuum chamber size is shown in column B of Table II. The optimum throughput occurs for a low plasma density of 10^8 ion/cm^3, giving a rather large sheath radius of 45 cm (the conformality of the resulting implant would depend on the amount of surface detail on the treated part). The batch size is increased greatly to 31 parts per batch, but the process time also increases to 5.8 hours since the pulse modulator power is still 25 kW. The resulting throughput is 5.3 parts/hr an increase of only 25% over the base system. This small return would probably not justify the cost of increasing the vacuum chamber size.

Column C of Table II shows the effect of an upgraded modulator on a system with the base 780 liter vacuum system. In this case the optimum plasma density occurs on the high side (10^{10} ion/cm^3) giving a small (14 cm) plasma sheath. The batch size is 33 parts and the overall throughput is 15 parts per hour. The non-trivial upgrade in pulse modulator may very well be justified by this increase in performance.

The results of calculation for the "super system" lie in column D of Table II. In this case the optimum plasma density is a moderate 10^9 ion/cm^3, yielding a sheath radius of 24 cm. The batch size is 110 parts with a total process time of 5.2 hours and a throughput of 21 parts per hour. This is an impressive factor of 5 increase over the base system and 50% greater than column C. This may or may not be worth the investment over the column C system. One main point of this series of calculations is that the greatest gains in PSII throughput can be made by increasing modulator performance. It should be noted that the a modulator with a total power of 100 kW and a peak current of 2000 A has not yet been produced.

Conclusions

The high throughput, low cost surface modification promised by plasma source ion implantation must be examined within the context of the system hardware and implications of the physics of the process. This paper has included a discussion of the basic PSII hardware, along with the implications on throughput of sheath propagation and secondary electron emission. As a specific example, the theoretical throughput of the system built by North Star Research Corporation was calculated and the effect of upgrades to this system were explored. The greatest gains in PSII system throughput can be made by increasing modulator performance.

Bibliography

J.R. Conrad, J.L Radtke, R.A. Dodd, F.J. Worzala and N.C. Tran, J. Appl. Phys **62**, 4591 (1987).

A. Chen, J.T. Scheuer, R.B. Alexander and J.R. Conrad, "Comparison Between Conventional and Plasma Source Ion Implanted Femoral Knee Components", J. Appl. Phys. **70**, 6757 (1991).

R.A. Reass, "Survey of High-Voltage Pulse Technology Suitable for Large-Scale Plasma Source Ion Implantation Processes", J. Vac. Sci. Technol. **B12**, 854 (1994).

J.T. Scheuer, M. Shamim and J.R. Conrad, "Model of Plasma Source Ion Implantation in Planar, Cylindrical and Spherical Geometries", J. Appl. Phys. **67**, 1241, (1990).

M. Shamim, J.T. Scheuer and J.R. Conrad, "Measurement of Spatial and Temporal Sheath Evolution for Spherical and Cylindrical Geometries in Plasma Source Ion Implantation", J. Appl. Phys. **69**, 2904 (1991).

M. Shamim, J.T. Scheuer, R.P. Fetherston and J.R. Conrad, "Measurement of Electron Emission Due to Energetic Ion Bombardment in Plasma Source Ion Implantation", J. Appl. Phys. **70**, 4756 (1991).

K.C. Walter, N. Yu, J.T. Scheuer and M.A. Nastasi, "Selected Mechanical and Tribological Properties of Chromium Modified Using Plasma Source Ion Implantation", submitted to 2nd International Workshop on Plasma Based Ion Implantation, Canberra, Australia, February, 1995.